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Surface Gravity Effects of Subterranean Tunnels

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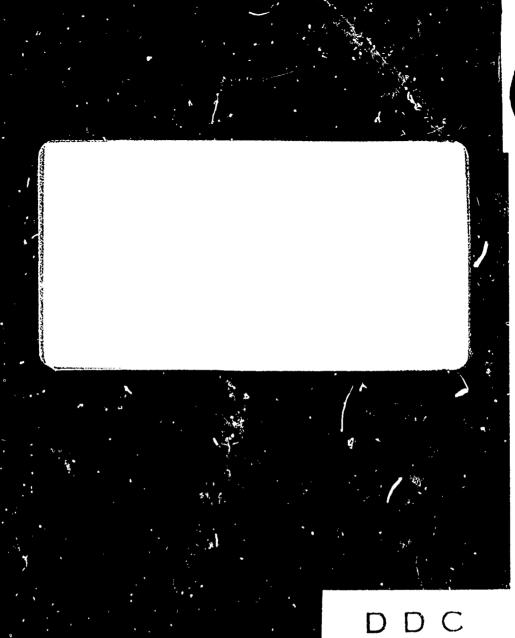
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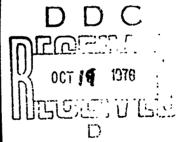
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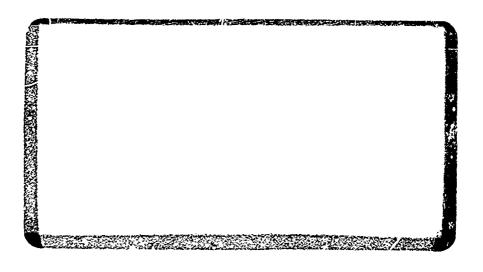


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This report determines the char	ige of six compor	
order tensor associated with the ear	th's gravity fie	eld as a result of the
following mass changes and condition	is: (1) A tunnel	16 km long is excavated for
below the earth's surface; (2) A veh the tunnel at the earth's surface; (ticle traveling a	a constant speed crosses
pare commer at the earth's surface! (ine resultina رق	t tensor component changes pret

computed and plotted; (4) The nomputations are repeated for tunnel depths of 30 a d 90 m; and (5) The problem may be inverted from one of subsurface mass removal to ose of mass addition above the corch's surface. The results of the report

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determine that (1) gradiometric detection of large tunnels to a depth of 30 m is feasible, (2) reliable detection of large tunnels deeper than 30 m imposes moderately sophiscicated data processing requirements, and (3) detection of tunnels deeper than 90 m is difficult.

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SURFACE GRAVITY EFFECTS OF SUBTERRANEAN TUNNELS

16 July 1976

Prepared for:

U.S. ARMY ENGINEER TOPOGRAPHIC LABORATORIES Fort Belvoir, Virginia 22060

Submitted in fulfillment of Contract No. DAAG53-76-M-5908

Approved For Public Related

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THE ANALYTIC SCIENCES CORPORATION Six Jacob Way Reading, Massachusetts 01867 J

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OVERVIEW

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PROBLEM STATEMENT AND METHOD OF APPROACH

- ERROR SOURCES WHICH REDUCE DETECTABILITY
- RESULTS
- SUMMARY AND CONCLUSIONS



Contract Number DAAG53-76M-5509 dated 8 June 1976

Work Statement for Purchasing Order

DETERMINATION OF SECOND ORDER TENSOR CHANGE AS A RESULT OF SPECIFIED MASS CHANGES

Determine the change of the six components of the symmetric second order tensor associated with the earth's gravity field as a result of the following mass changes and conditions:

- 1. A tunnel 16 km long and having a diameter of 5 m is excavated 6 m below the earth's surface, and the resulting mass with density $\rho = 2.6$ g cm⁻³ is removed to infinity.
- 2. A vehicle traveling at the constant speed of 10 km h⁻¹ crosses the tunnel at the earth's surface 7 km from a tunnel end point at intersection angles of 90°, 60°, and 30°.
- 3. The resulting tensor component changes should be computed and plotted as a function of time and for changes equal or greater than 10^{-2} Eotvos.
- 4. The computations specified above should be repeated for the tunnel depths of 30 m and 90 m.
- 5. For the purpose of computational simplicity, the problem may be inverted from one of subsurface mass removal to one of mass addition above the earth's surface.

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GRADIOMETRIC DETECTION OF HORIZONTAL SUBTERRANEAN TUNNELS - PROBLEM DEFINITION

HOW FEASIBLE IS TUNNEL DETECTION BASED ON SURFACE GRAVITY GRADIENT MEASUREMENTS?

"QUICK LOOK" ANALYSIS INPUTS (SPECIFIED IN SOW)

- CYLINDRICAL TUNNEL DEPTH (y) = 6 m, 30 m, 90 m
- TUNNEL RADIUS (a) = 2.5 m
- TUNNEL LENGTH $(2z_0 + \Delta z) = 16 \text{ km}$
- GRADIOMETER VEHICLE VELOCITY = 10 km/hr
- ANGLE BETWEEN VEHICLE TRACK AND TUNNEL AXIS (HORIZONTAL PROJECTION) = 30° , 60° , 90°
- DISTANCE TO NEAREST TUNNEL END FROM AXIAL POINT BELOW THE SURFACE POINT AT WHICH VEHICLE CROSSES (z_{o}) = 7 km (Figure on next page.)
- FLAT TERRAIN



GRADIOMETRIC TUNNEL DETECTION GEOMETRY

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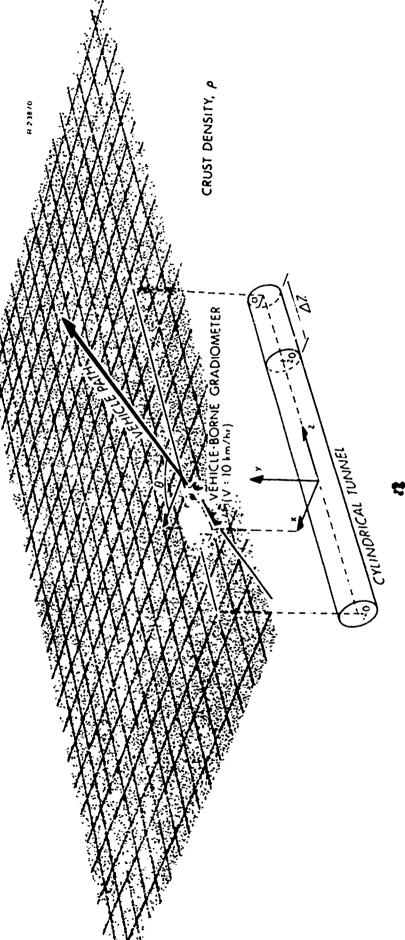
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METHOD OF ANALYSIS

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- DIVIDE PROBLEM INTO EQUAL LENGTH CYLINDERS ON EACH SIDE OF CROSSING POINT. TREAT ASYMMETRICAL EXTENSION TO ONE END SFPARATELY
- TAKE ADVANTAGE OF FAVORABLE AXIAL ASPECT RATIO VIA GAUSS' LAW TO FIND THE SYMMETRICAL GRAVITY FIELD BY SURFACE INTEGRATION
- MODEL THE (FAR-REMOVED) ASYMMETRICAL END EXTENSION AS A POINT MASS
- FIND THE GRADIENT FIELDS BY ANALYTIC DIFFERENTIATION
- POINT MASS MODEL PROVIDES UPPER BOUND ON EFFECT OF ASYMMETRICAL CYLINDER END SINCE ACTUAL FIELD ATTENUATES MORE SLOWLY THAN POINT MASS FIELD (DUE TO PRESENCE OF HIGHER ORDER SPHERICAL HARMONICS)
- USE ASYMMETRICAL FIELD CALCULATION TO MEASURE END EFFECTS NOT MODELED IN GAUSS' LAW SOLUTION OF SYMMETRICAL PROBLEM
- EXPRESS TOTAL GRADIENT AS SUM OF "SYMMETRICAL" AND "ASYMMETRICAL" TERMS
- TRANSFORM RESULTS INTO "ALONG-TRACK, UP, CROSS-TRACK" COORDINATES



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EQUATIONS OF THE GRAVITY FIELD

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SYMMETRICAL PORTION $(-z_O \text{ TO } + z_O)$

$$\mathbf{g}_{\text{Sym}} = \frac{2\pi a^2 \rho G}{x^2 + y^2} \begin{bmatrix} x \\ y \\ 0 \end{bmatrix}$$

ASYMMETRICAL PORTION (z_o TO $z_o + \Delta z_o$)

$$g_{asy} = \frac{\pi a^2 \Delta z \rho G}{\left[x^2 + y^2 + \left(z - z_0 - \frac{\Delta z}{2}\right)^2\right] 3/2}$$

WHERE G IS THE UNIVERSAL GRAVITATIONAL CONSTANT

*x, y, z COORDINATES



PREVIEW OF RESULTS FOR OPTIMAL ENCOUNTER GEOMETRY (MAGNITUDES ONLY)

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 3.2×10^{-5} 4.8×10^{-5} ASYMMETRIC 2.8×10^{-5} MAXIMUM GRAVITY GRADIENT ELEMENT (EU) SYMMETRIC 190 0.84 9.2 MAXIMUM GRAVITY DISTURBANCE COMPONENT (mgal) 1.2×10^{-5} 1.6×10^{-5} 1.1×10^{-5} ASYMMETRIC 2.3×10^{-2} 7.6×10^{-3} 1.1×10^{-1} SYMMETRIC (meters) TUNNEL DEPTH 30 90 ဖ

ERROR SOURCES WHICH REDUCE DETECTABILITY

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POSSIBLE ERROR SOURCES ADVERSE TO TUNNEL DETECTION

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ERROR SOURCE	ERROR MAGNITUDE	IMPACT ON GRADIOMETRIC MEASUREMENT
GRADIOMETER ERROR WHITE NOISE (10 sec avg)	1* - 10 EU [‡]	NONE IF VEHICLE MOVES VERY SLOWLY OR HALTS FOR GRADIENT MEASUREMENT
LOW FREQUENCY RANDOMNESS	1 - 20 [†] EU	SIGNIFICANT REDUCTION PROBABLE WITH OPTIMAL FILTERING
TUNNEL DEVIATION FROM HORIZONTAL, CYLINDRICAL GEOMETRY	UNKNOWN	PROBABLY NOT SEVERE EXCEPT FOR RIGHT ANGLE TURNS (GRADIENTS OF FINE STRUCTURE ATTENUATE RAPIDLY)
EARTH'S ANOMALOUS GRADIENT FIELD		
RMS VARIATION	10 - 30 EU	EFFECT WILL BE REDUCED SOME- WHAT DUE TO SHORT TRACK LENGTH
HIGH DENSITY LOCAL GRADIENT ANOMALIES (ORE BODIES, NATURAL CAVES)	POSSIBLY > 100 EU	MAY REQUIRE SIGNATURE CORRELA- TION TECHNIQUES FOR DISCRIMI- NATION

*GOAL FOR CURRENT GRADIOMETER DEVELOPMENT PROGRAMS

**BEST DEMONSTRATED TO DATE IN LABORATORY

**FONE EUTVOS UNIT (EU) = 10^9 sec^2



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TRACK LENGTH (meters)	RMS GRADIENT VARIATION (AVERAGED OVER TRACK - EU)
10	1 BU
20	2.2 EU
200	4.5 EU

BASED ON SIMPLIFIED ANALYSIS USING

- FIRST-ORDER MARKOV GRADIENT MODEL
- RMS GRADIENT = 20 EU
- GRADIENT CORRELATION DISTANCE = 4 km

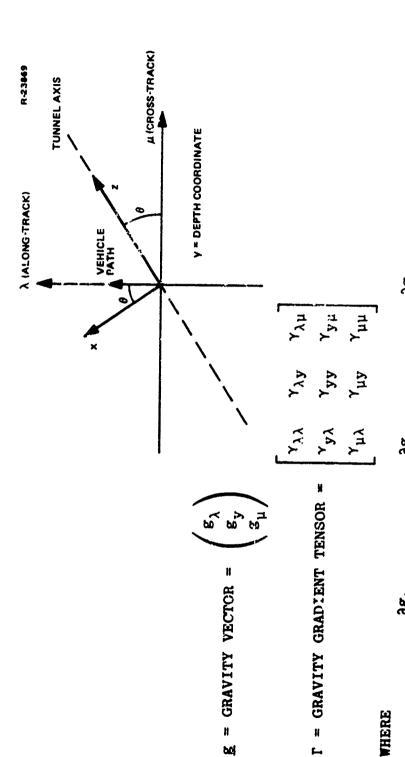
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RESULTS

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DEFINITIONS AND NOTATION



O AND 30° ENCOUNTER ANGLES GRAVITY VECTOR COMPONENTS

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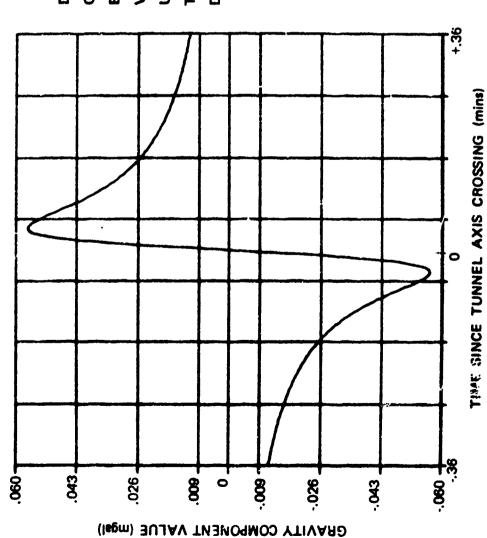
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SURFACE GRAVITY VECTOR COMPONENT FROM TUNNEL



DEPTH TO TUNNE; AXIS = 6m
GRAVITY COMPONENT ELEMENT = 9,
ENCOUNTER ANGLE (0) = 0°
VEHICLE VELOCITY = 10 km/hr
UNIFORM CRUSTAL DENSITY = 2.6 g/cm³
TUNNEL LENGTH = 16 km
DISTANCE TO NEAREST END = 7 km



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SURFACE GRAVITY VECTOR COMPONENT FROM TUNNEL

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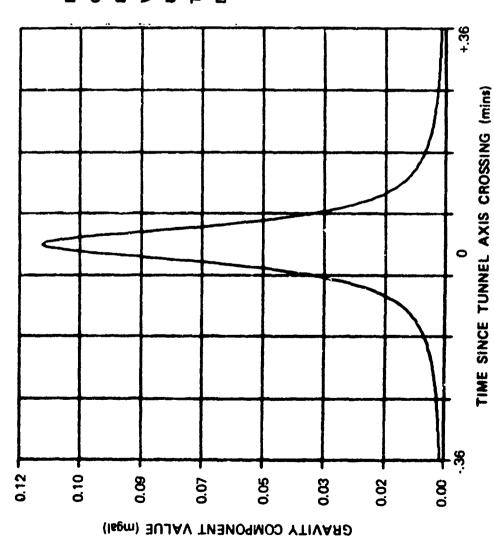
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DEPTH TO TUNNEL AXIS = 6m

GRAVITY COMPONENT ELEMENT = 9,

ENCOUNTER ANGLE (\$\theta\$) = 0°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm³

TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km



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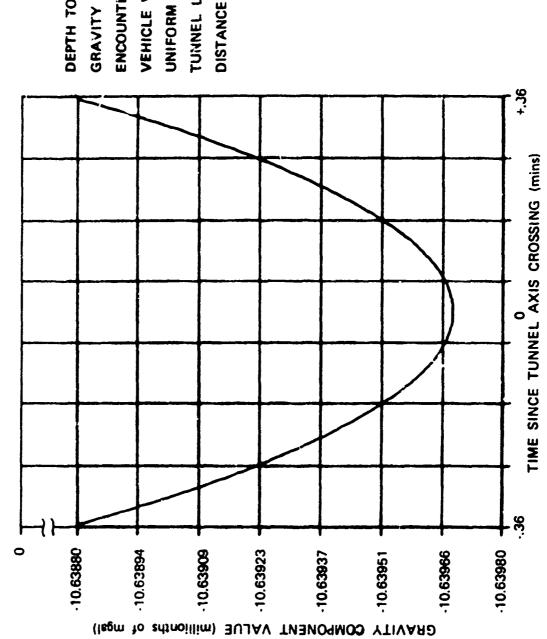
SURFACE GRAVITY VECTOR COMPO SENT FROM TUNNEL

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Table 1



GRAVITY COMPONENT ELEMENT = 9_µ

ENCOUNTER ANGLE (8) = 0°

VEHICLE VELOCITY = 10 km/hr

UNIFORM CRUSTAL DENSITY = 2.6 g/cm³

TUNNEL LENGTH = 16 km

DISTANCE TO NEAREST END = 7 km



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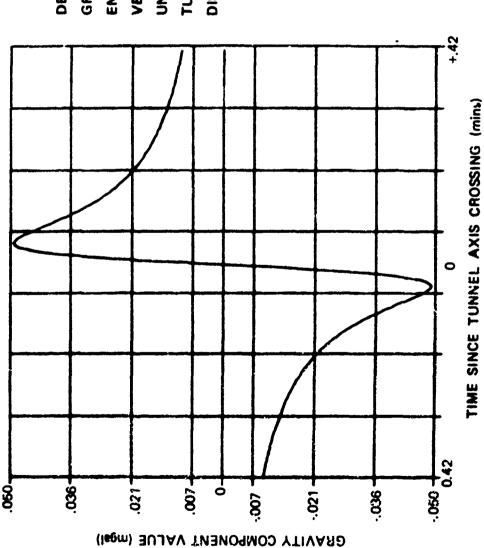
SURFACE GRAVITY VECTOR COMPONENT FROM TUNNEL

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DEPTH TO TUNNEL AXIS = 6mGRAVITY COMPONENT ELEMENT = g_{λ} ENCOUNTER ANGLE (θ) = 30^{0} VEHICLE VELOCITY = 10 km/hrUNIFORM CRUSTAL DENSITY = 2.6 g/cm^{3} TUNNEL LENGTH :: 16 kmDISTANCE TO NEAREST END = 7 km



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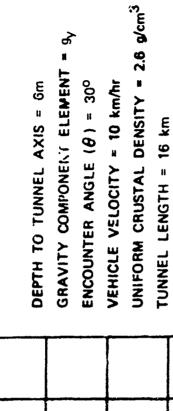
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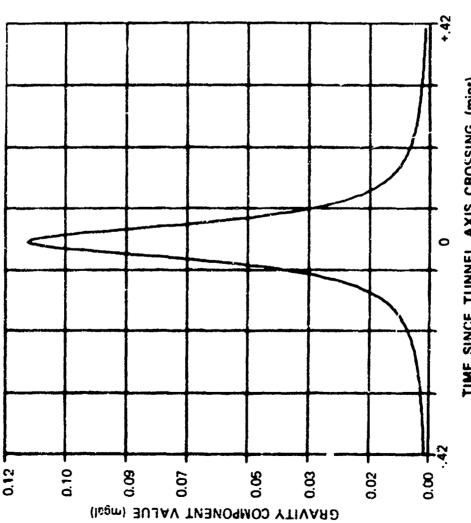
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DISTANCE TO NEAREST END = 7 6m

TIME SINCE TUNNEL AXIS CROSSING (mins)



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的人,我们就是这种的时候,我们就是我们的人,我们就是我们的人,我们就是我们的人,我们们的人,我们也是我们的人,我们也是这个人,这个人是我们的人,也是这样,也是是

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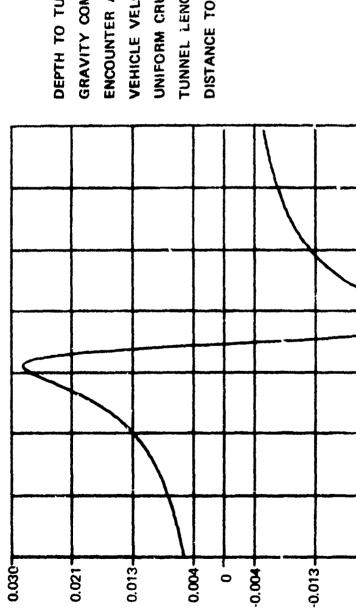
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SURFACE GRAVITY VECTOR COMPONENT FROM TUNNEL



GRAVITY COMPONENT VALUE (mgal)

UNIFORM CRUSTAL DENSITY = 2.6 g/cm³ 4 DISTANCE TO NEAREST END = 7 km GRAVITY COMPONENT ELEMENT DEPTH TO TUNNEL AXIS = 6m ENCOUNTER ANGLE $(\theta) = 30^{\circ}$ VEHICLE VELOCITY = 10 km/hr TUNNEL LENGTH = 16 km



TIME SINCE TUNNEL AXIS CROSSING (mins)

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O° ENCOUNTER ANGLE (GRAVITY GRADIENTS) DEPTH = 6 METERS

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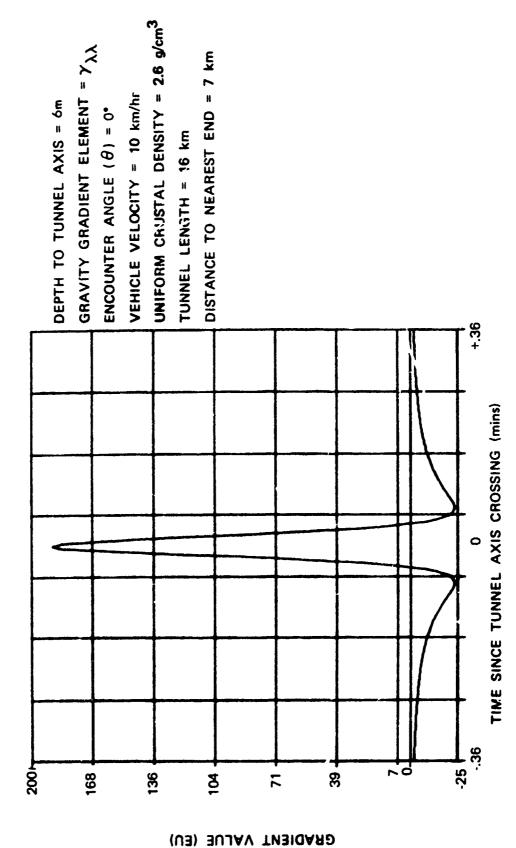
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SURFACE GRAVITY GRADIENT FROM TUNNEL



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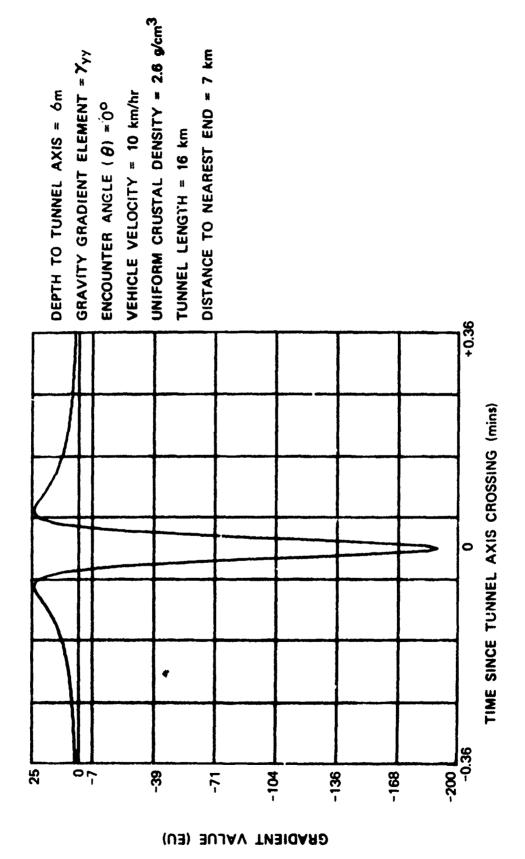
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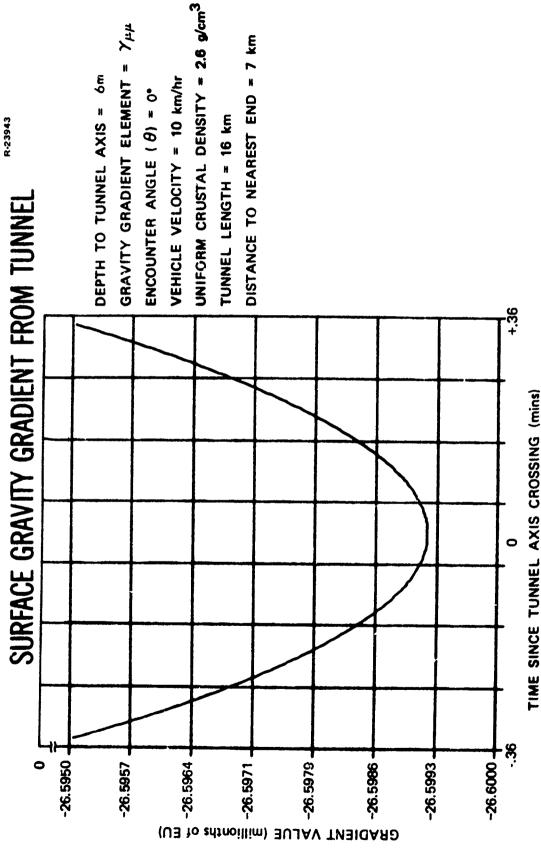




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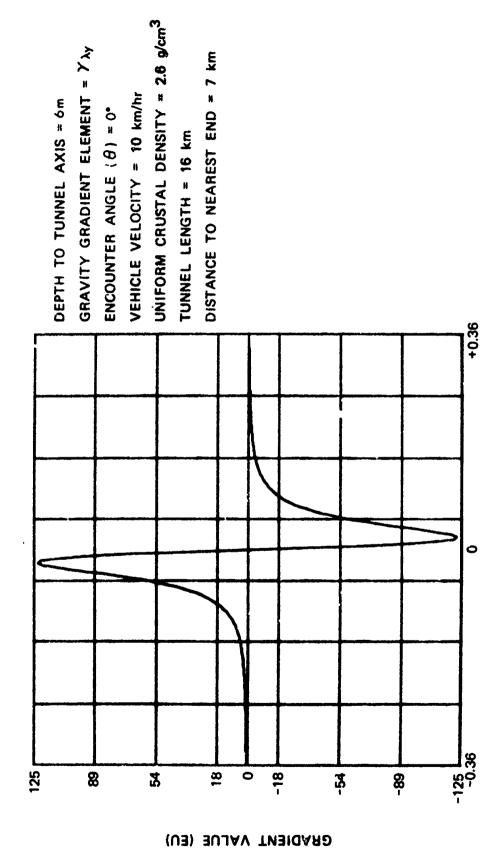
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TIME SINCE TUNNEL AXIS CROSSING (mins)

SURFACE GRAVITY GRADIENT FROM TUNNEL

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DEPTH TO TUNNEL AXIS = 6mGRAVITY GRADIENT ELEMENT = $7_{\lambda\mu}$ ENCOUNTER ANGLE (θ) = 0° VEHICLE VELOCITY = 10 km/hr
UNIFORM CRUSTAL DENSITY = 2.6 g/cm³
TUNNEL LENGTH = 16 km

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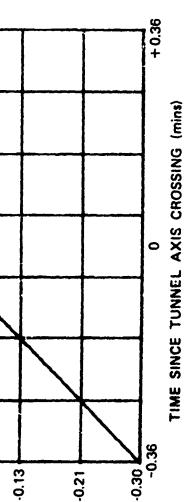
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GRADIENT VALUE (millionths of EU)

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DISTANCE TO NEAREST END = 7 km



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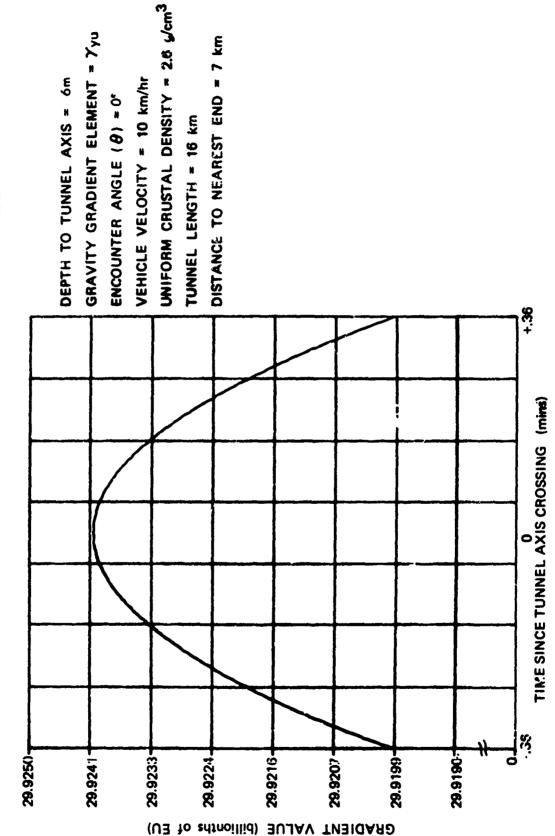
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DEPTH = 6 METERS 30° ENCOUNTER ANGLE

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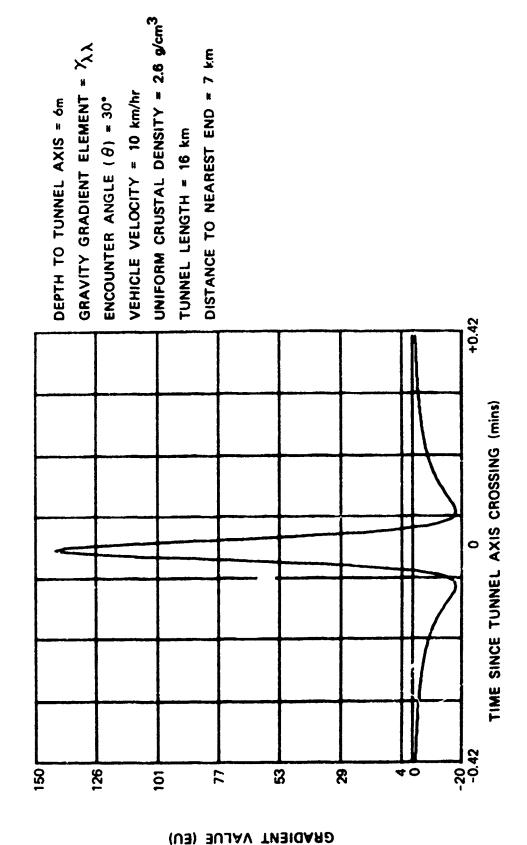
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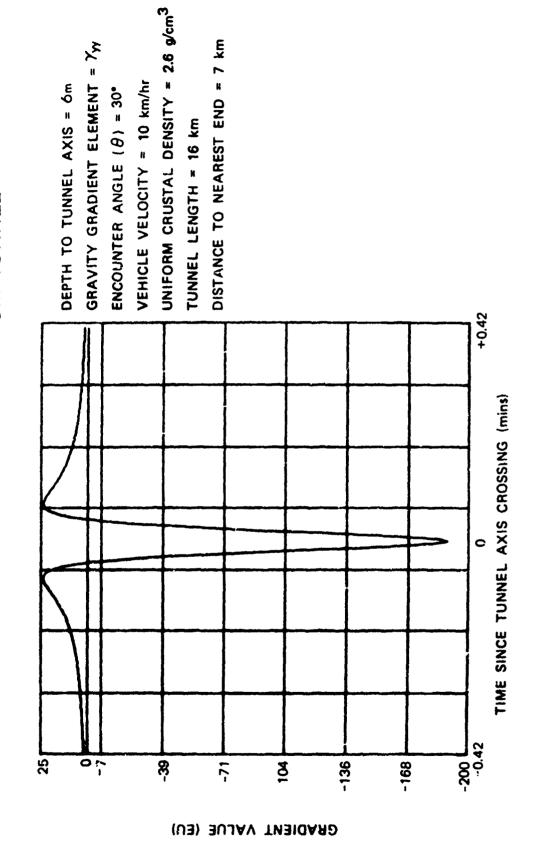
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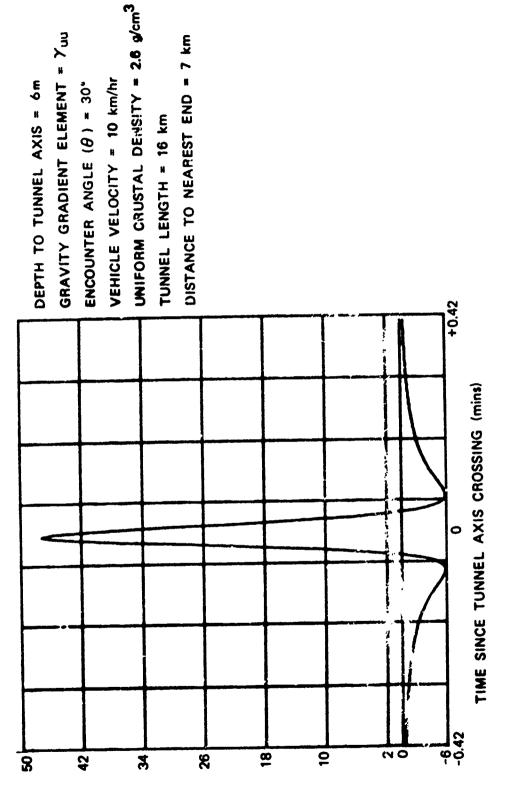
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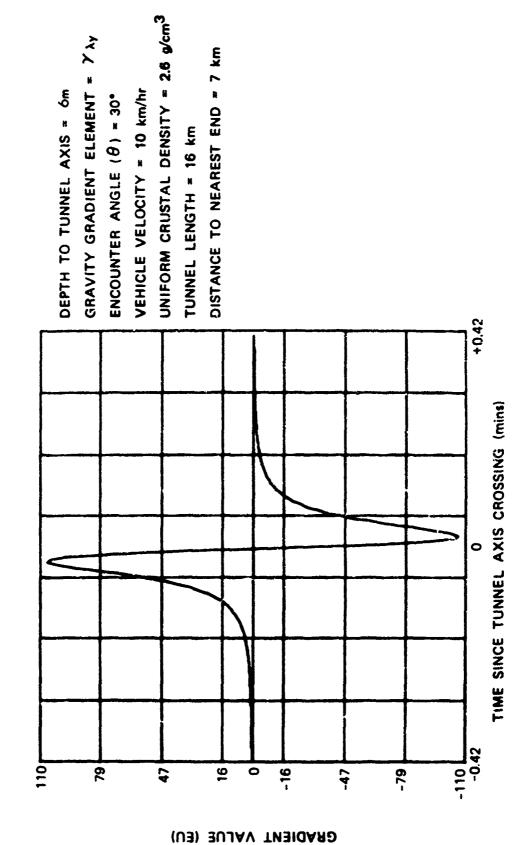
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SURFACE GRAVITY GRADIENT FROM TUNNEL



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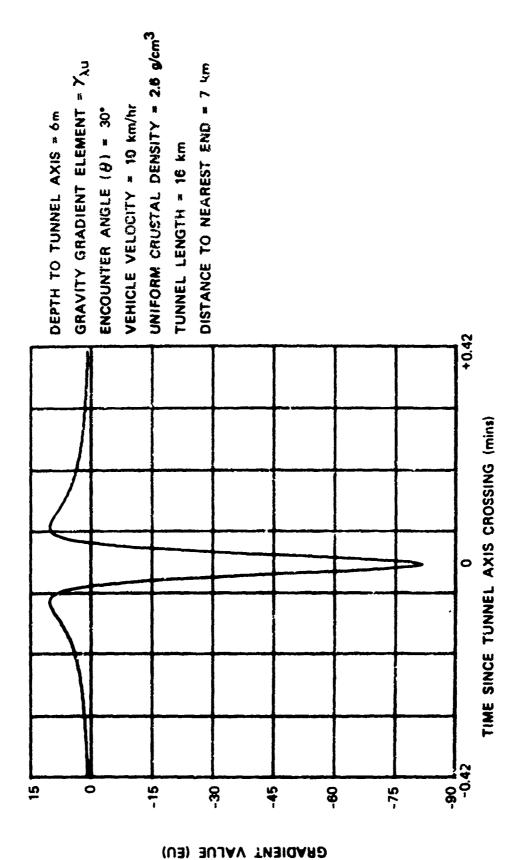
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SURFACE GRAVITY GRADIENT FROM TUNNEL.



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SURFACE GRAVITY GRADIENT FROM TUNNEL

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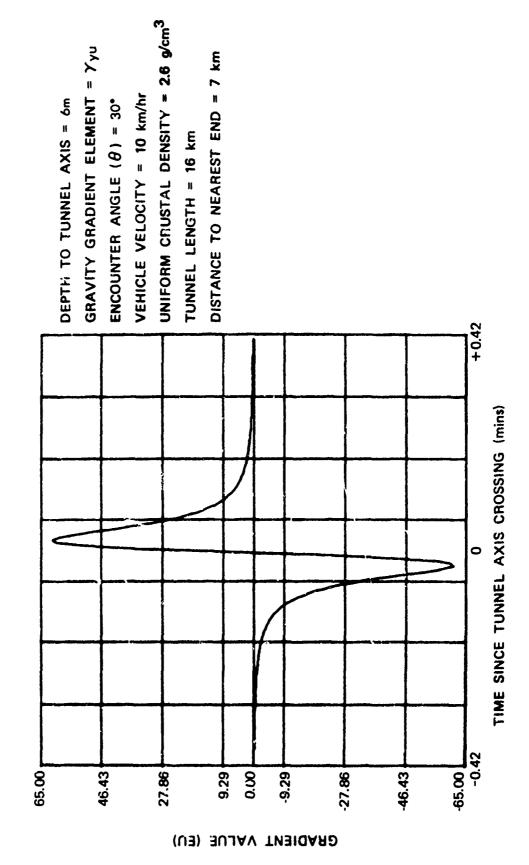
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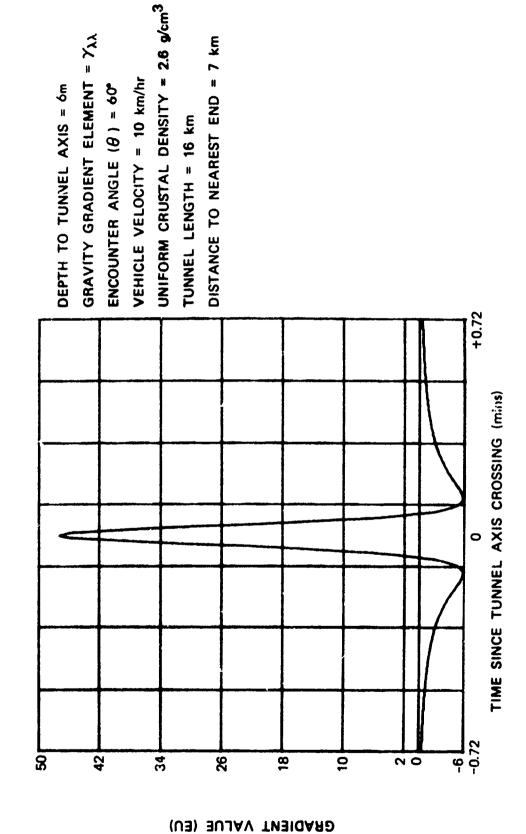
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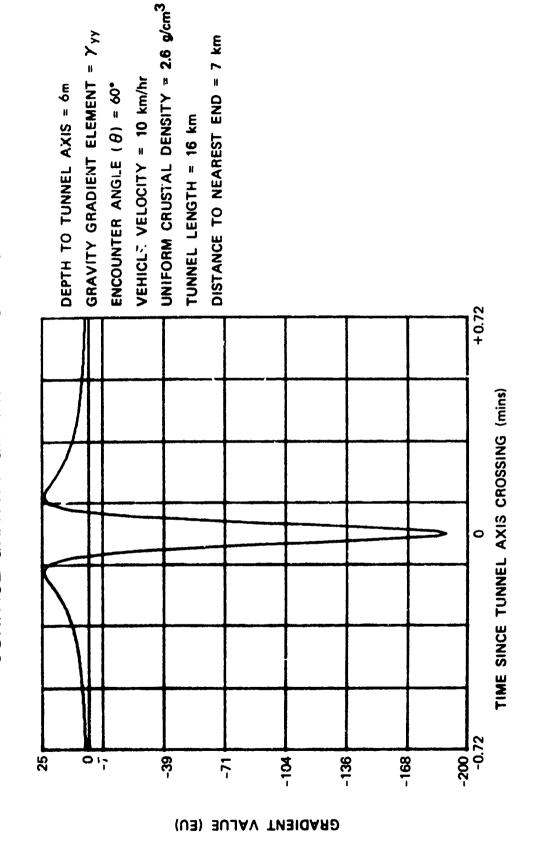
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SURFACE GRAVITY GRADIENT FROM TUNNEL



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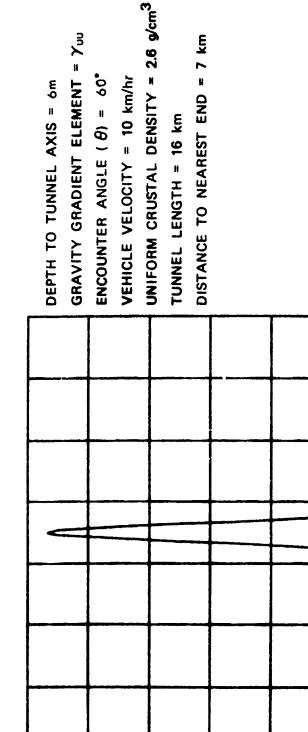
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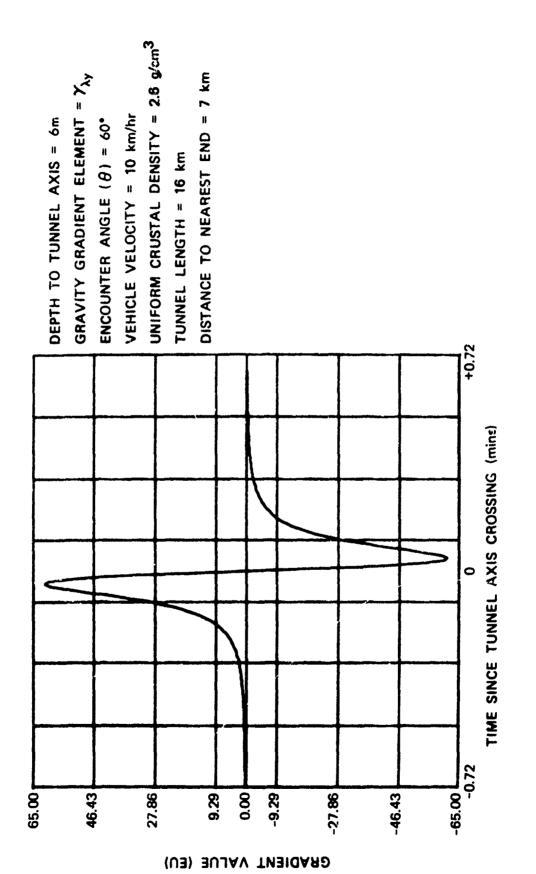
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TIME SINCE TUNNEL AXIS CROSSING (mins)

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SURFACE GRAVITY GRADIENT FROM TUNNEL



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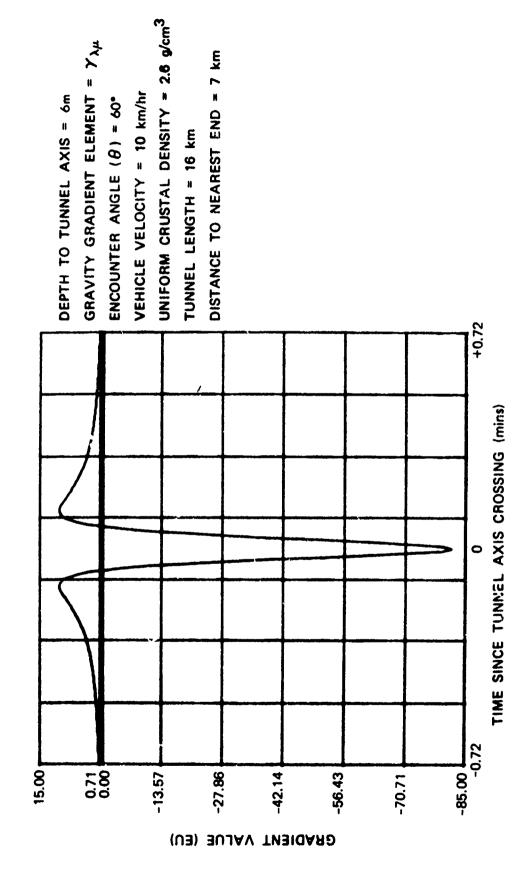
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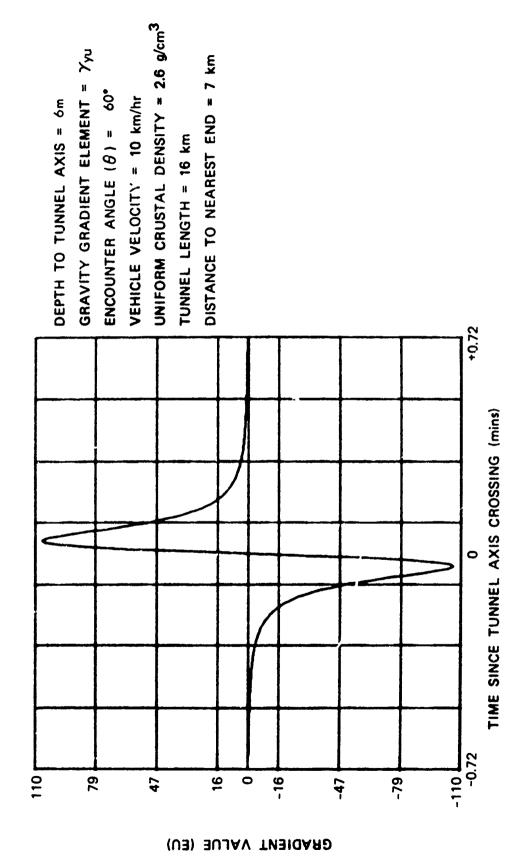
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SURFACE GRAVITY GRADIENT FROM TUNNEL





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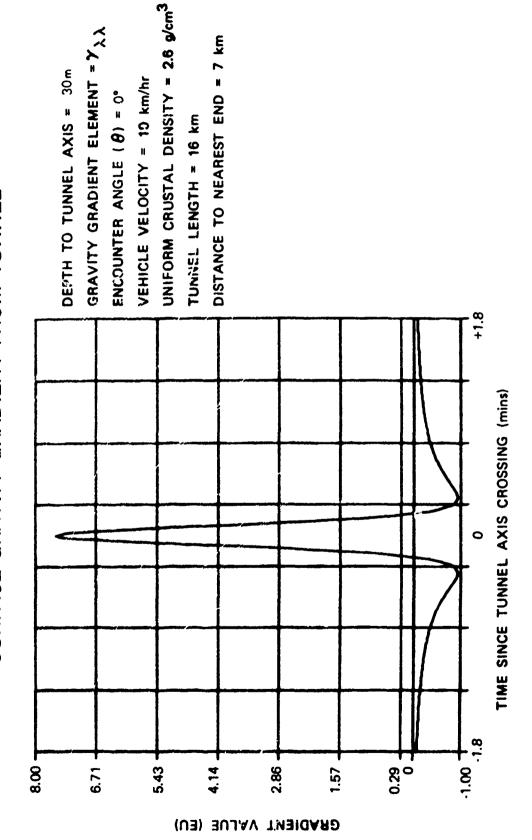
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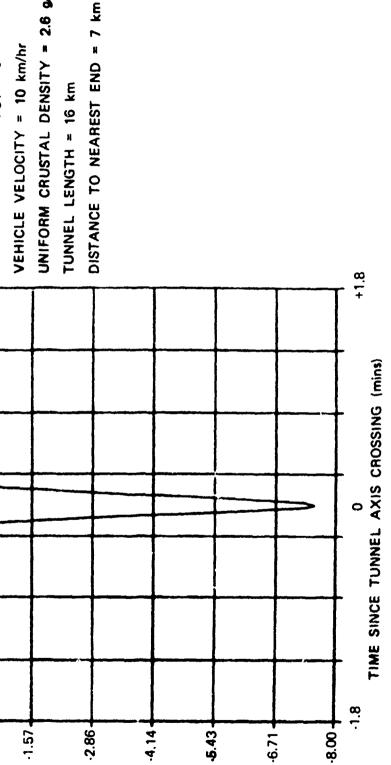
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DEPTH TO TUNNEL AXIS = 30m GRAVITY GRADIENT ELEMENT = Y_{yy} ENCOUNTER ANGLE (θ) = 0° VEHICLE VELOCITY = 10 km/hr UNIFORM CRUSTAL DENSITY = 2.6 g/cm³ TUNNEL LENGTH = 16 km



GRADIENT VALUE (EU)

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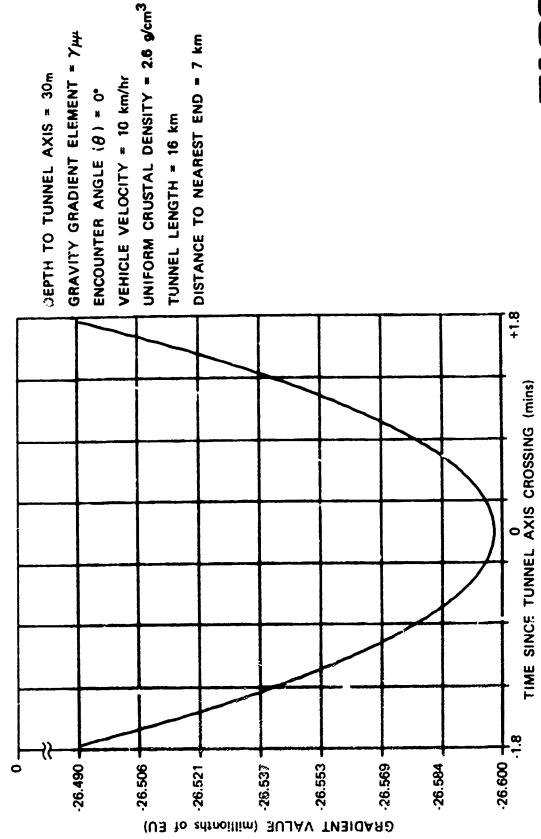
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SURFACE GRAVITY GRADIENT FROM TUNNEL

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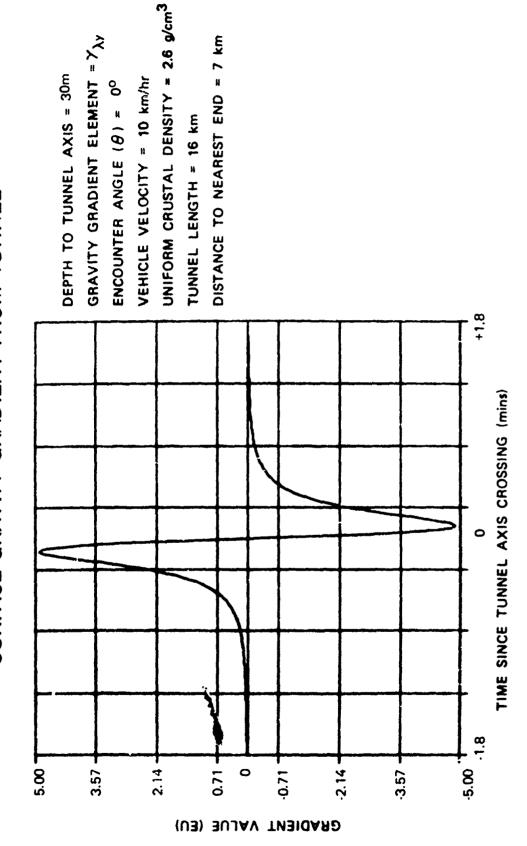
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GRADIENT VALUE (millionths of EU)

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DISTANCIE TO NEAREST END = 7 km





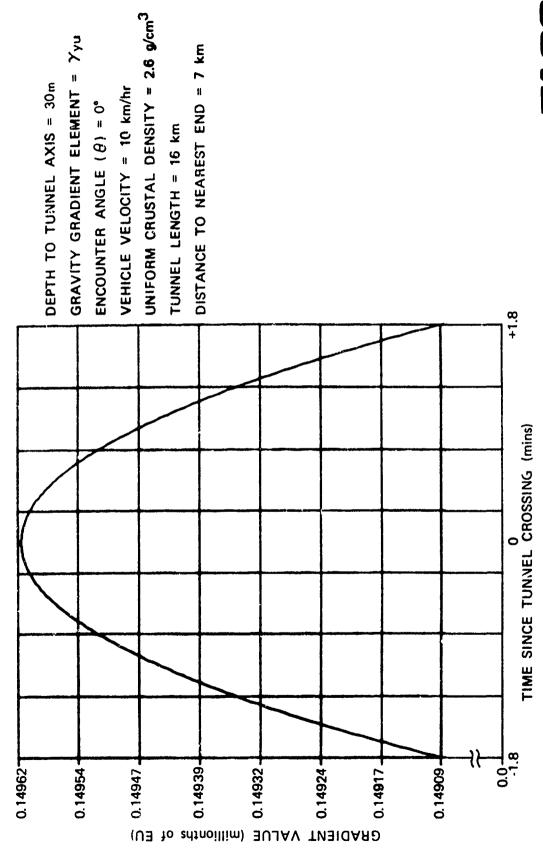
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SURFACE GRAVITY GRADIENT FROM TUNNEL





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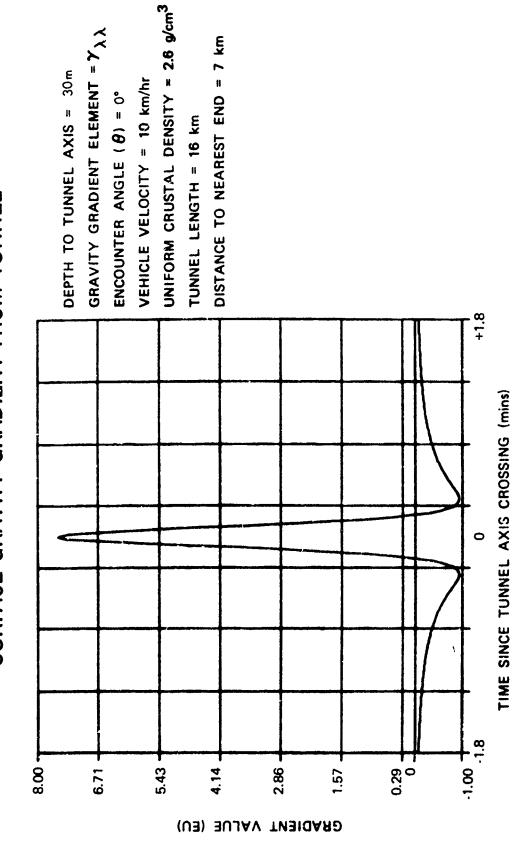
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SURFACE GRAVITY GRADIENT FROM TUNNEL



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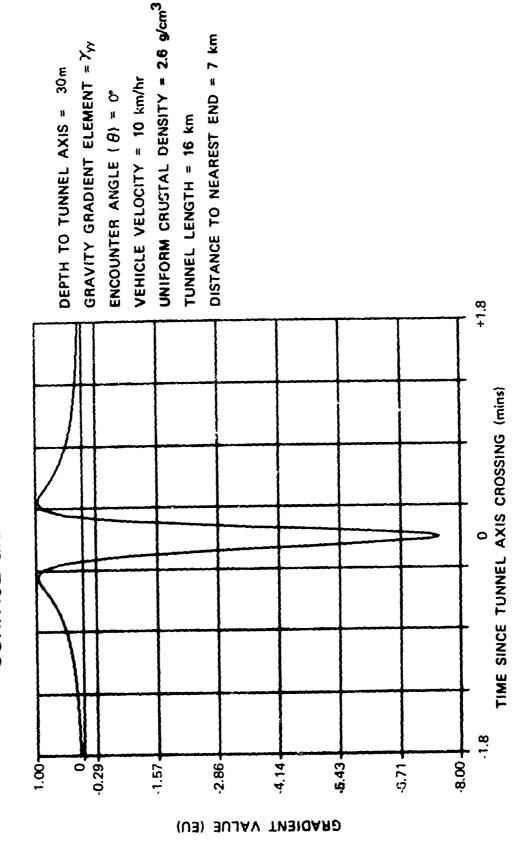
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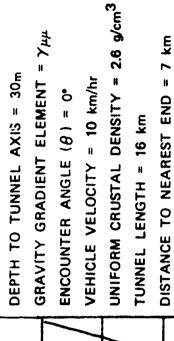
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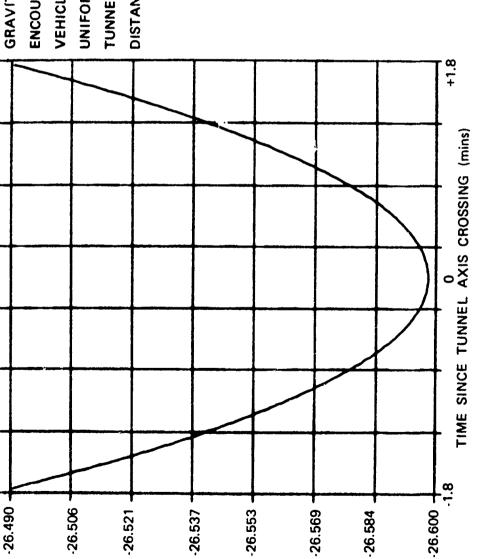
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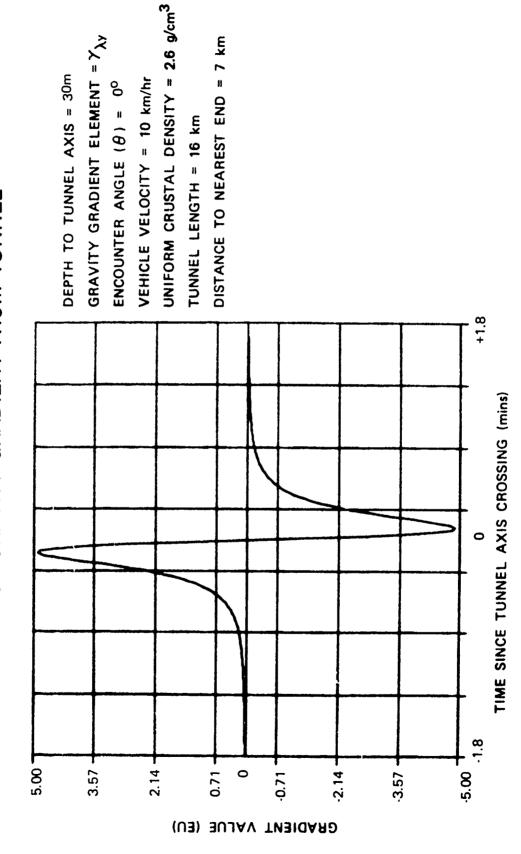
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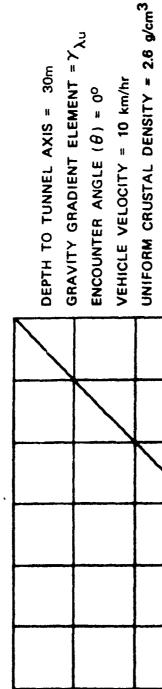
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DISTANCE TO NEAREST END = 7 km

TUNNEL LENGTH = 16 km



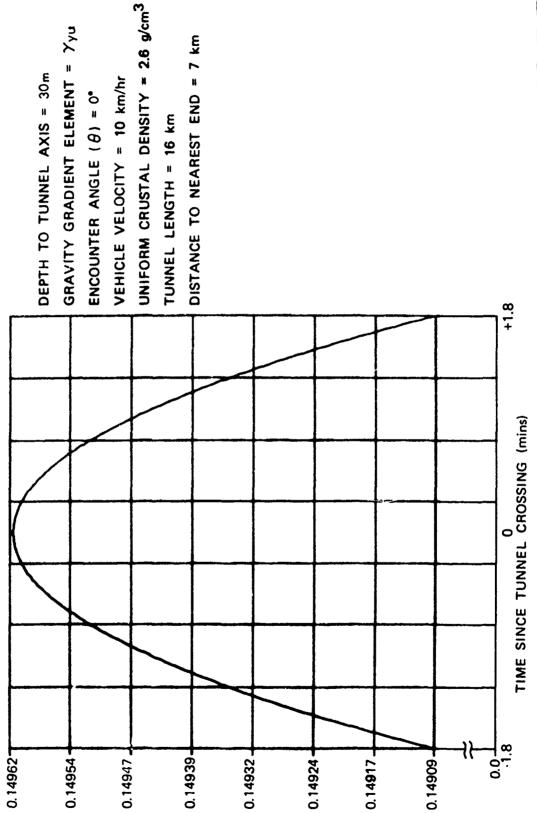
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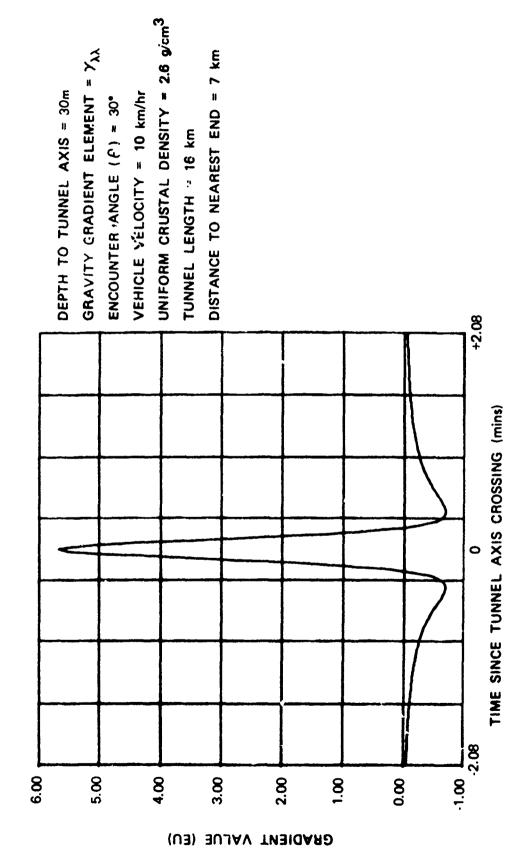
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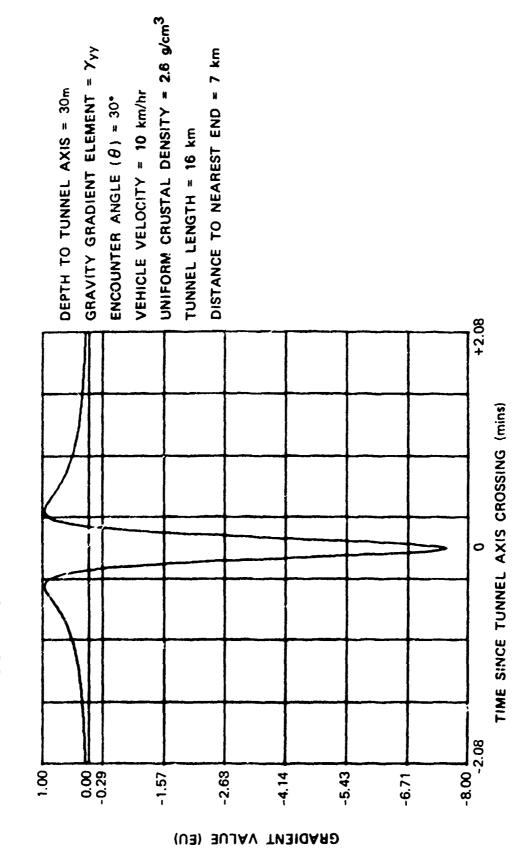
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SURFACE GRAVITY GRADIENT FROM TUNNEL



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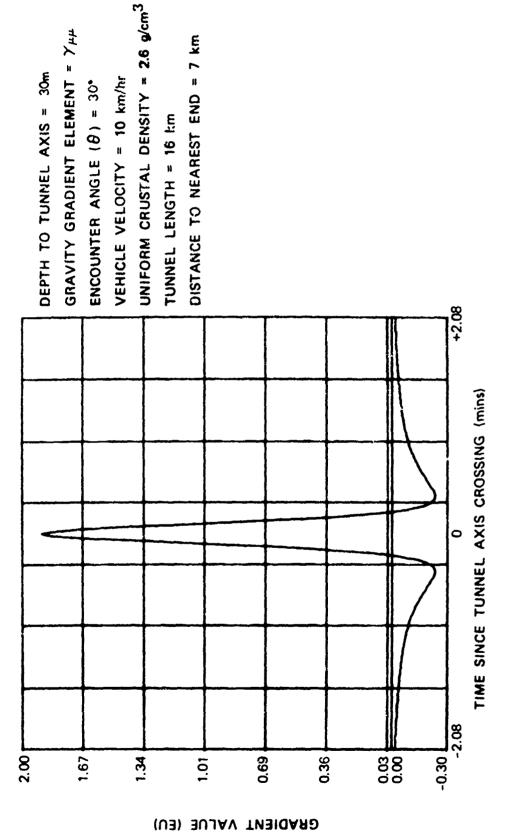
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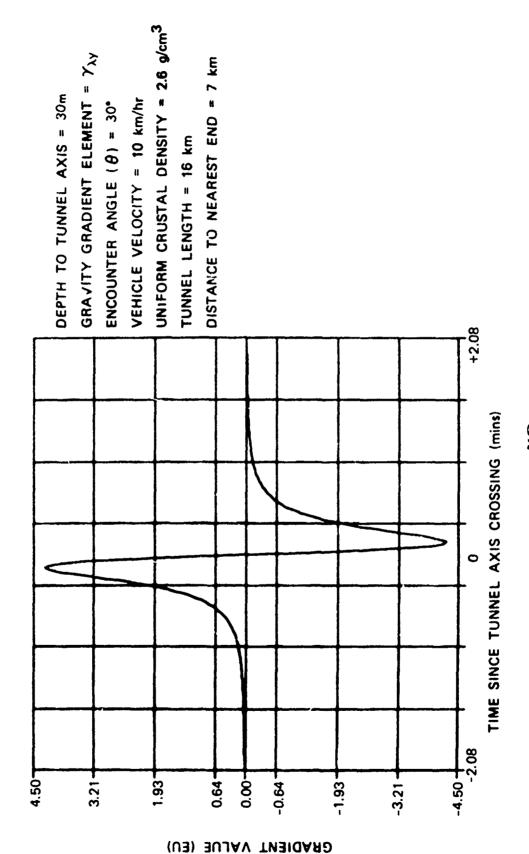
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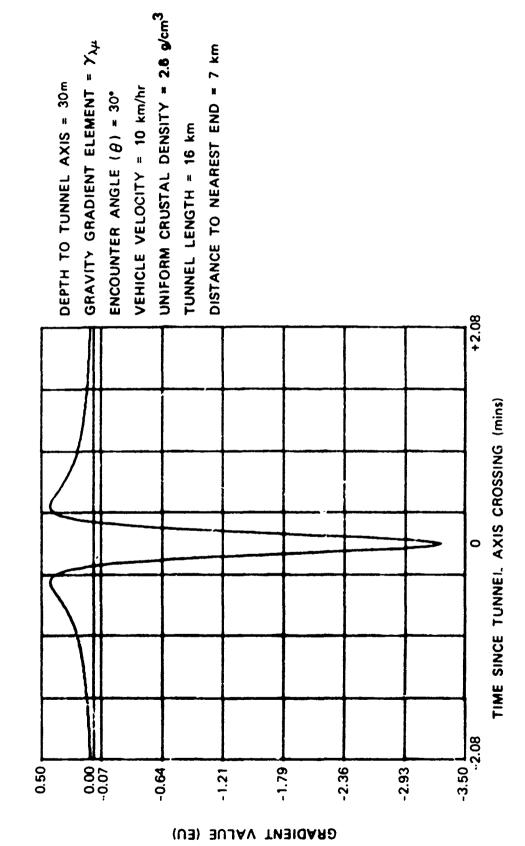
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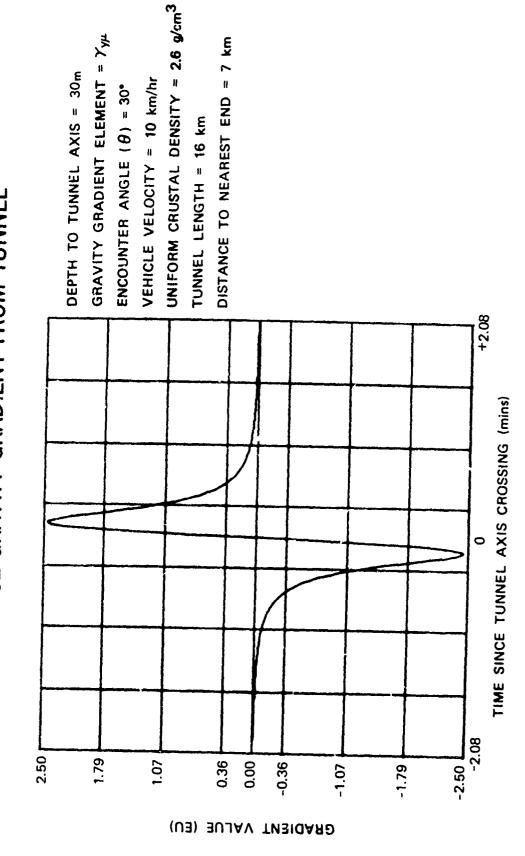




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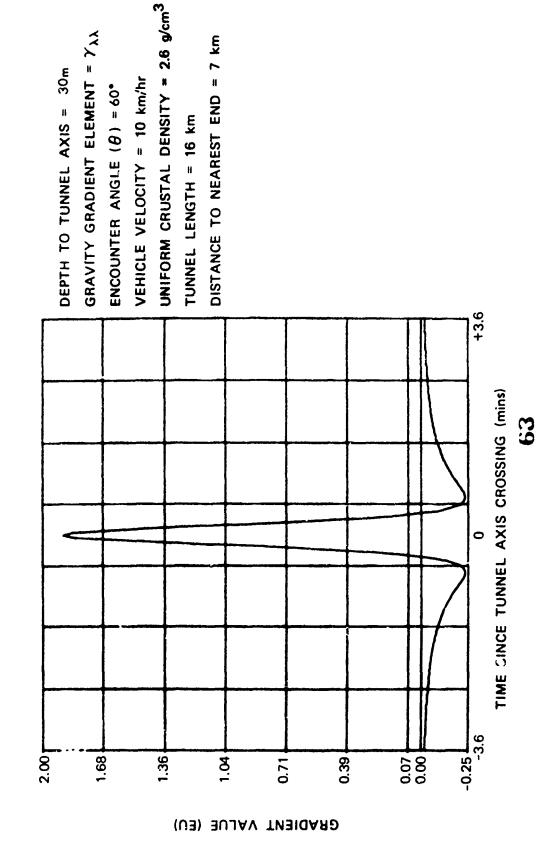
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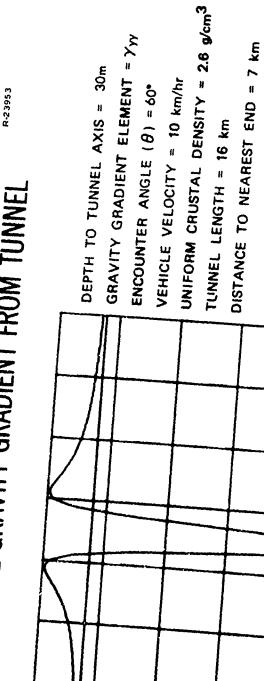


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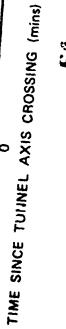
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GRADIENT VALUE (EU)

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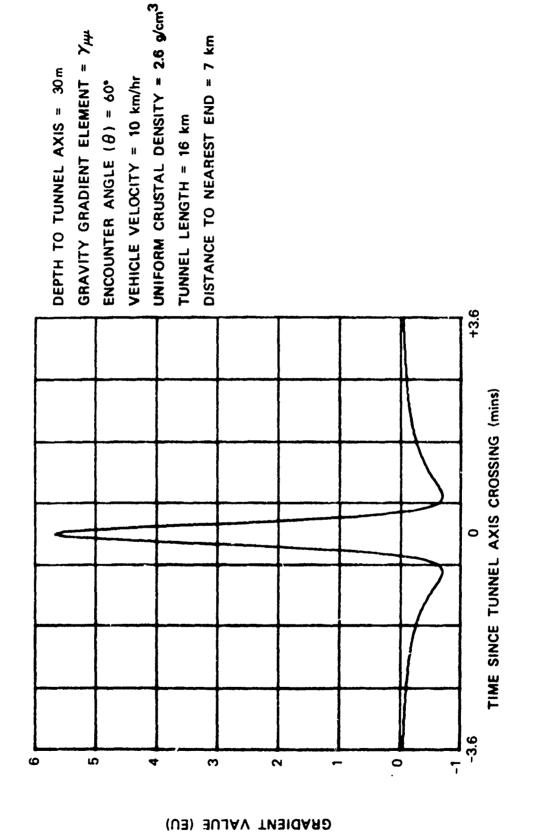
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SURFACE GRAVITY GRADIENT FROM TUNNEL

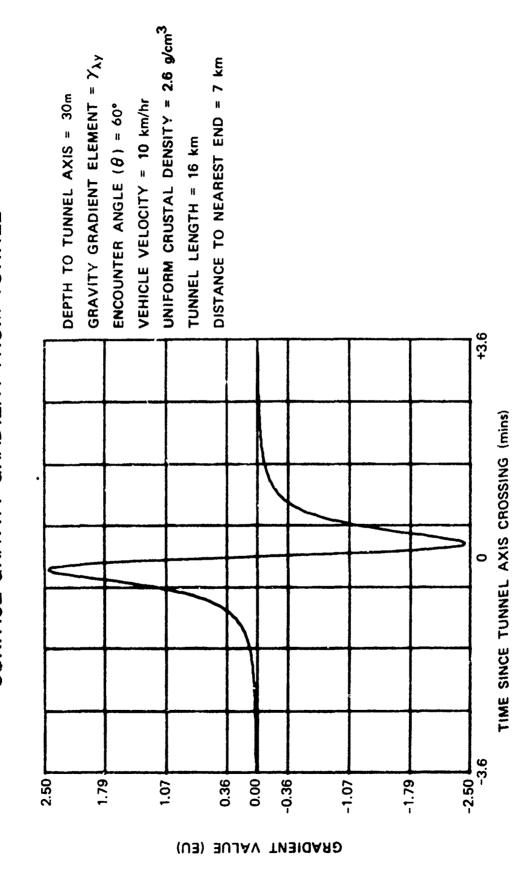




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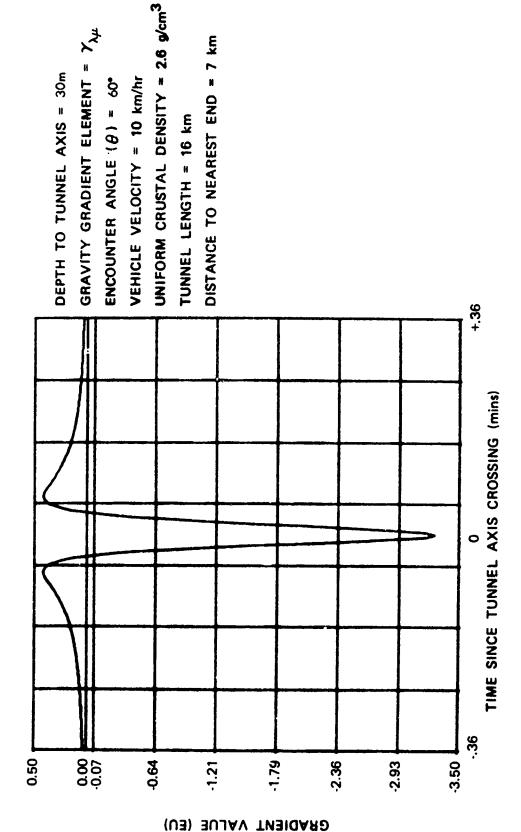
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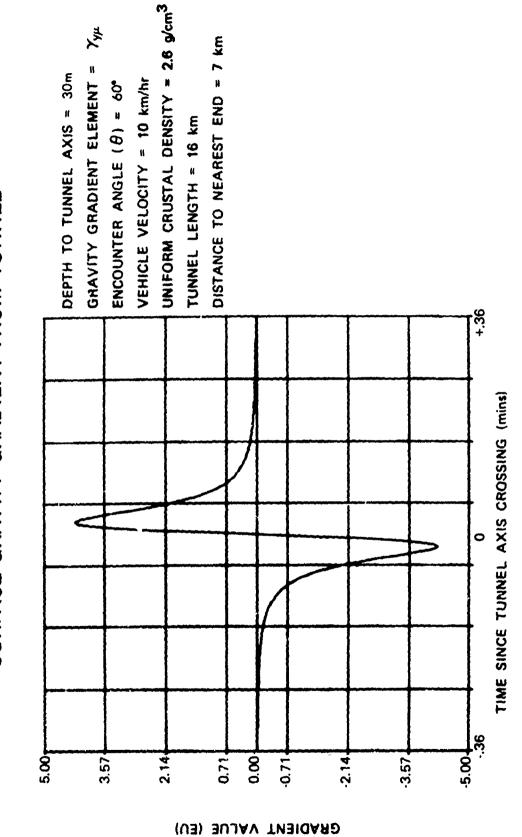
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SURFACE GRAVITY GRADIENT FROM TUNNEL





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DEPTH = 90 METERS 0° ENCOUNTER ANGLE

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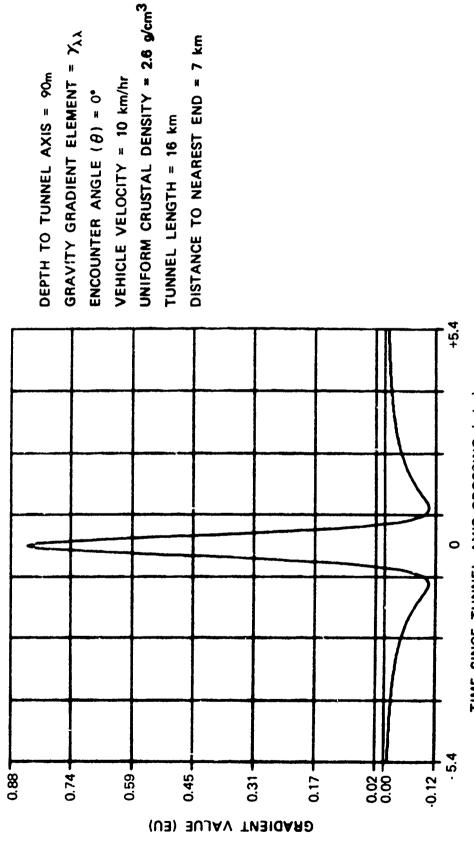
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SURFACE GRAVITY GRADIENT FROM TUNNEL



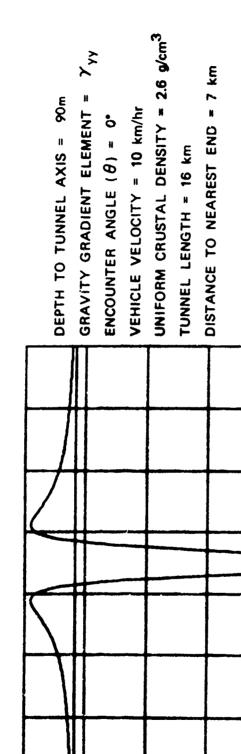
TIME SINCE TUNNEL AXIS CROSSING (mins)



SURFACE GRAVITY GRADIENT FROM TUNNEL

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GRADIENT VALUE (EU)

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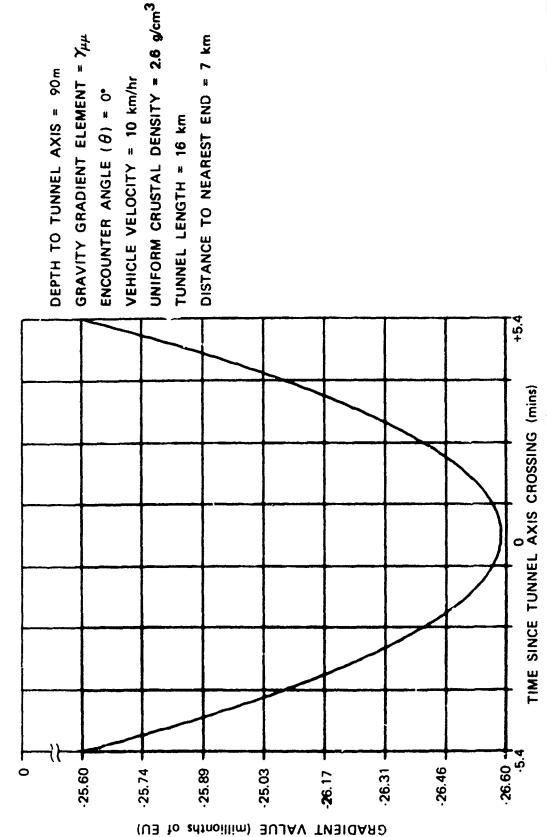
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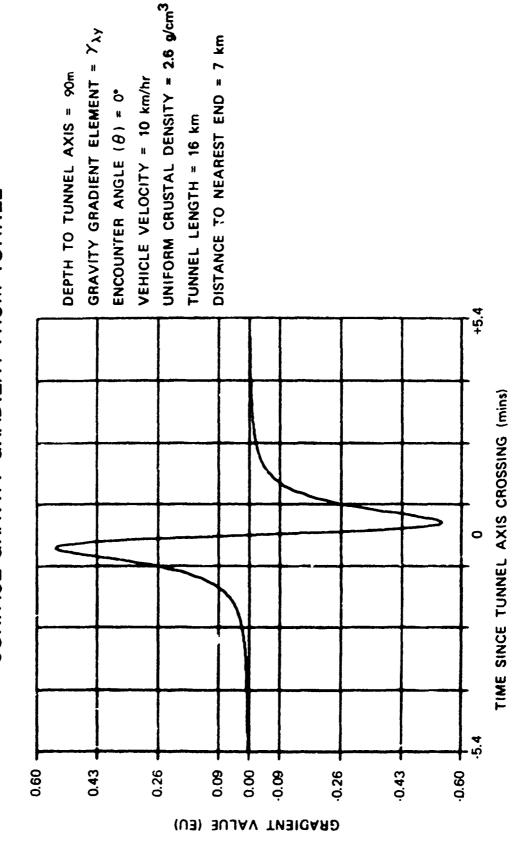
SURFACE GRAVITY GRADIENT FROM TUNNEL

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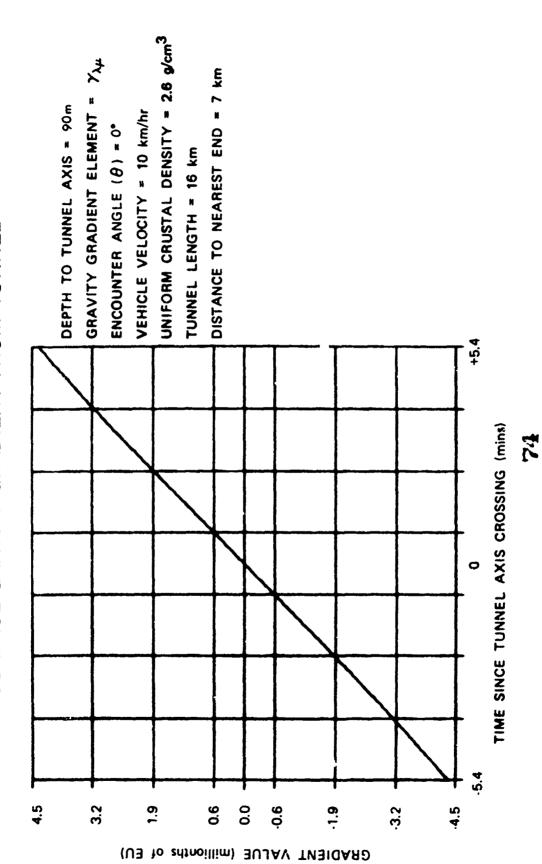
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SURFACE GRAVITY GRADIENT FROM TUNNEL



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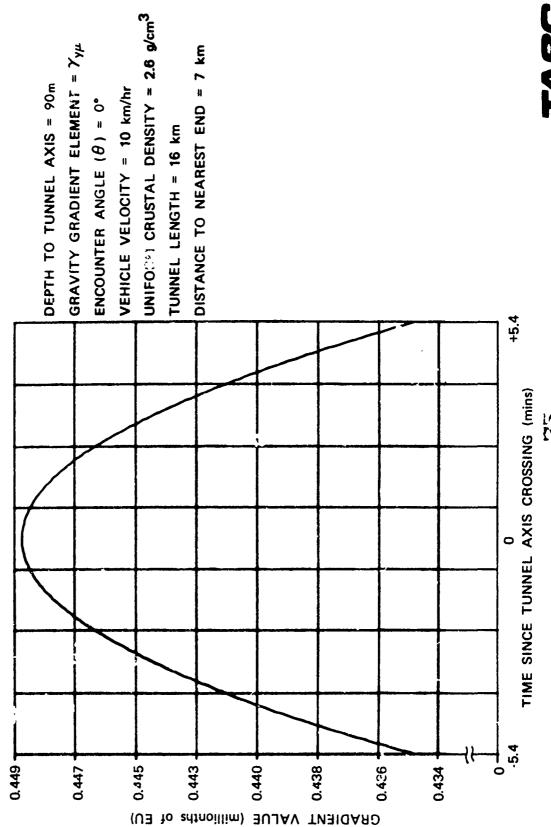
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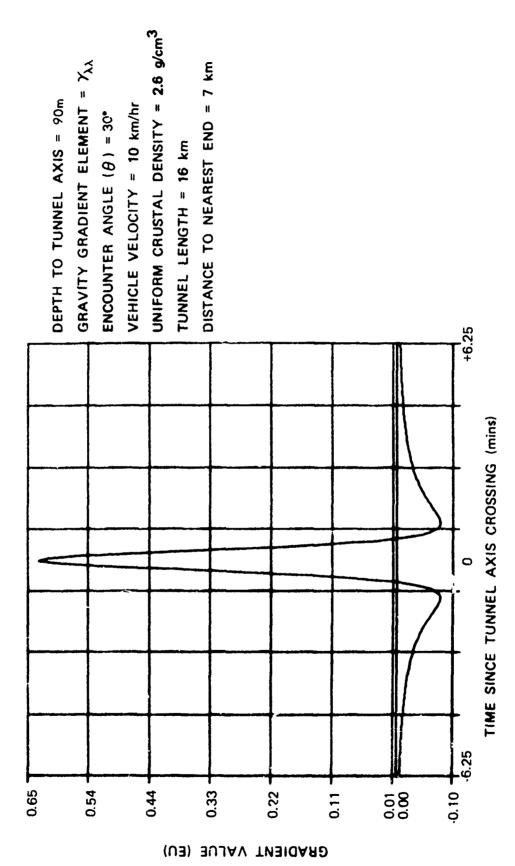
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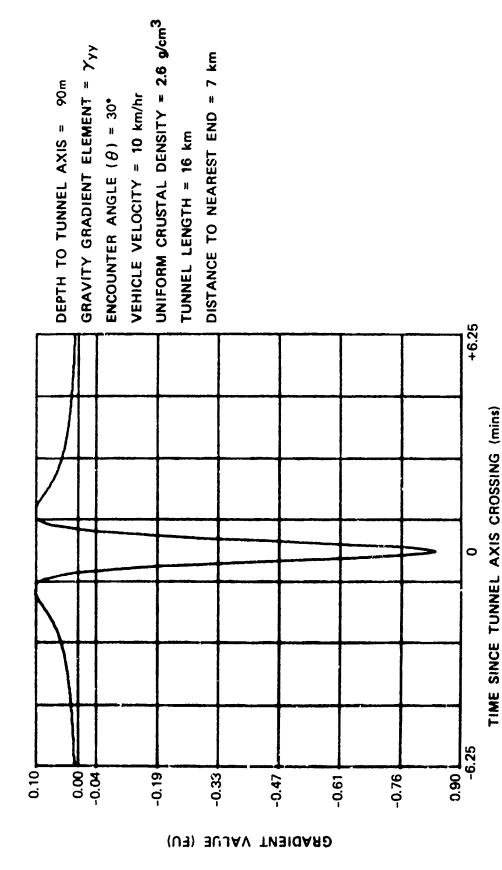




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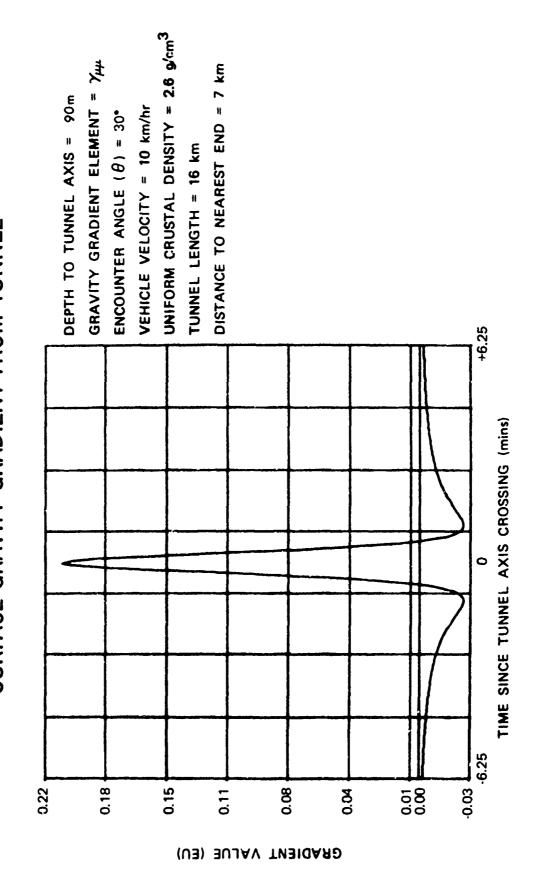
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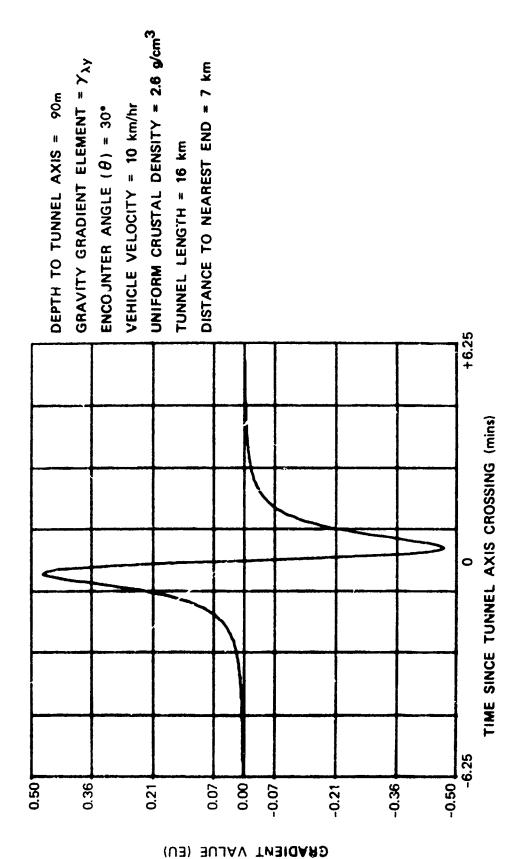
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VEHICLE VELOCITY = 10 km/hr
UNIFORM CRUSTAL DENSITY = 2.6 g/cm³
TUNNEL LENGTH = 16 km

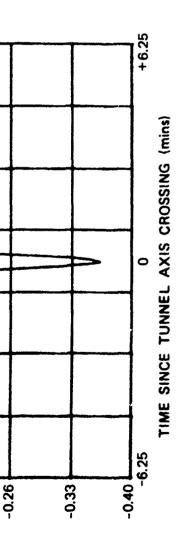
DISTANCE TO NEAREST END = 7 km

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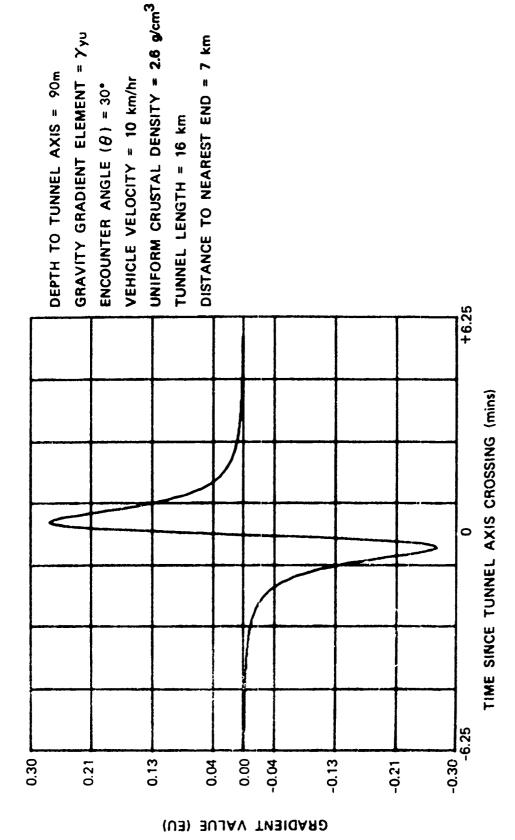
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GRADIENT VALUE (EU)





SURFACE GRAVITY GRADIENT FROM TUNNEL



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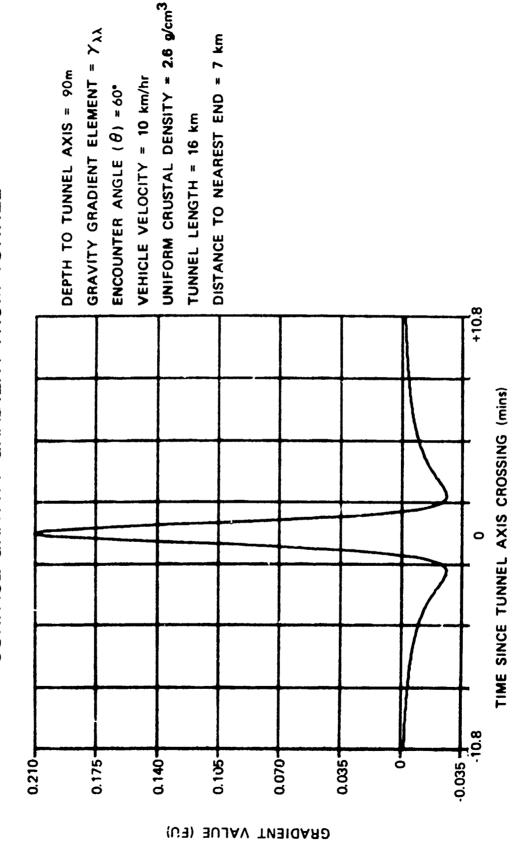
DEPTH = 90 METERS 60° ENCOUNTER ANGLE

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SURFACE GRAVITY GRADIENT FROM TUNNEL



SURFACE GRAVITY GRADIENT FROM TUNNEL

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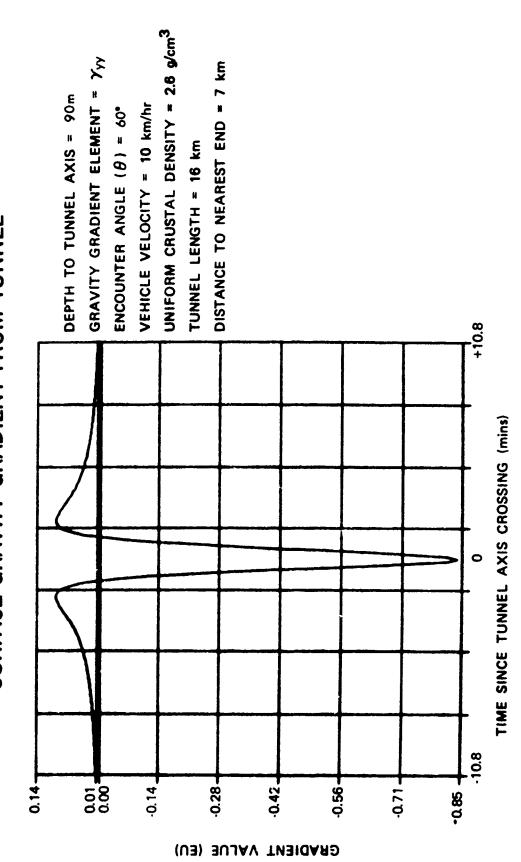
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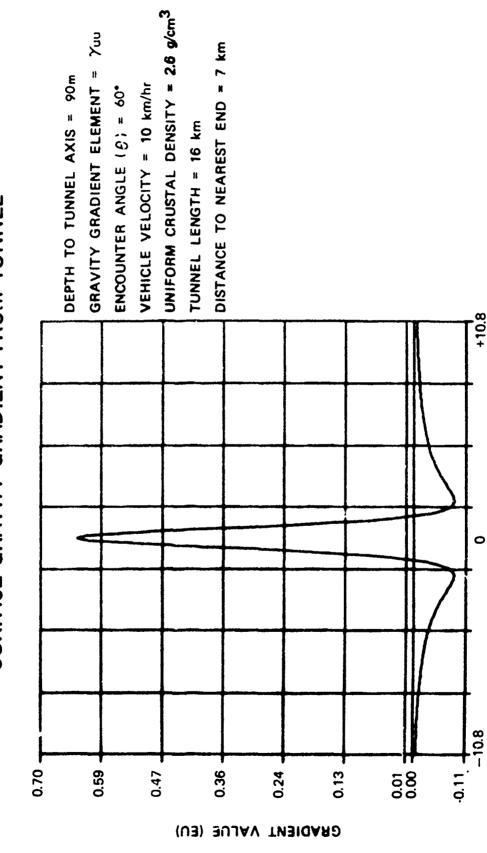


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SURFACE GRAVITY GRADIENT FROM TUNNEL

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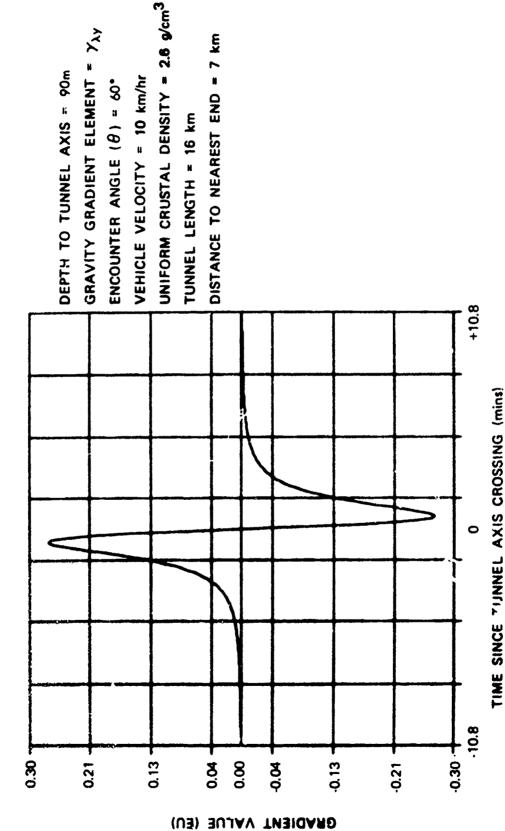
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TIME SINCE TUNNEL AXIS CROSSING (mins)



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SURFACE GRAVITY GRADIENT FROM TUNNEL



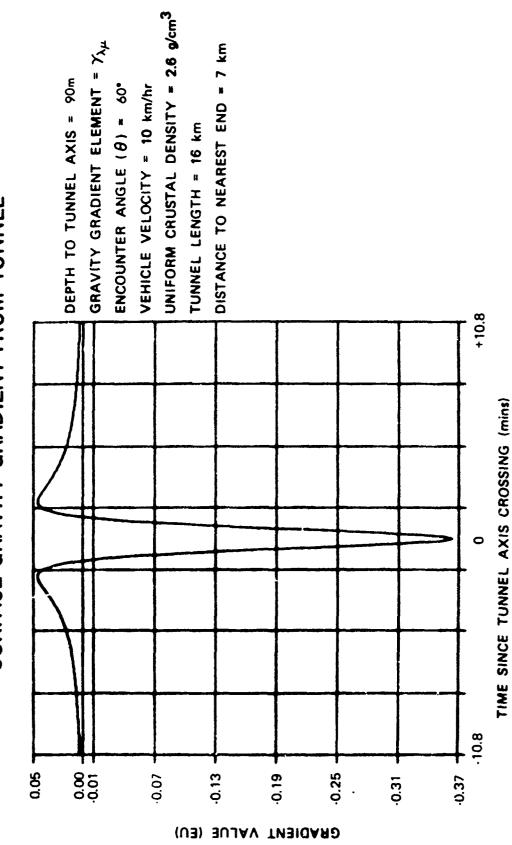


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4 × 5 × 5 × 5 × 6

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SURFACE GRAVITY GRADIENT FROM TUNNEL



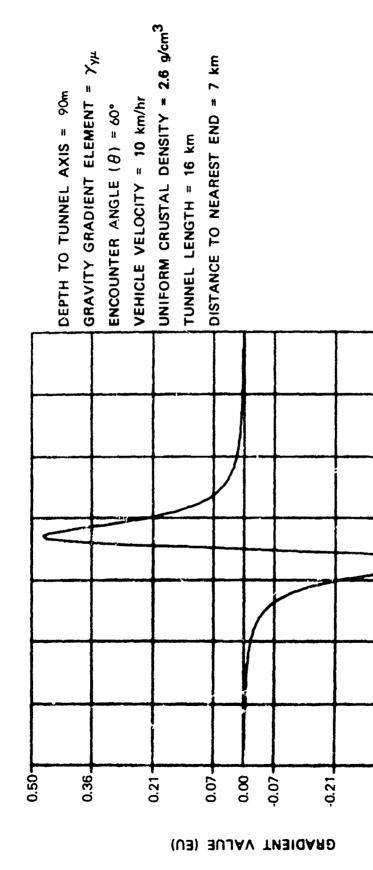
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SURFACE GRAVITY GRADIENT FROM TUNNEL





TIME SINCE TUNNEL AXIS CROSSING (mins)

.10.8

-0.50

-0.36

+10.8

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GRAVITY AND GRAVITY GRADIENTS DEPEND LINEARLY ON THE AMOUNT OF SOURCE MASS

AS TOTAL MASS OF A UNIFORM, CONSTANT LENGTH CYLINDRICAL BODY VARIES THE RADIUS SQUARED FOR CYLINDER JF RADIUS r (METERS), GRADIENTS AND GRAVITY VECTOR COMPONENTS DETERMINED IN THIS STUDY APPLY IF MULTIPLIED BY THE FACTOR

SIMILARLY FOR A DENSITY OF THE SURROUNDING MEDIUM OTHER THAN 2.6 g/cm³, RESULTS SHOULD BE MULTIPLIED BY THE FACTOR

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WHERE P IS THE DENSITY IN g/cm³

SUMMARY AND CONCLUSIONS

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SUMMARY

THE REPORT OF THE PROPERTY OF

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PEAK GRADIENT SIGNAL STRENGTH AT BEST AND WORST* ENCOUNTER GEOMETRY

GRAI	VITY GR	GRAVITY GRADIENT ELEMENT	VALUES OF 8 FOR BEST	9 FOR BEST		MAXIMUM	VALUE O	MAXIMUM VALUE OF GRADIENT (EU)	YT (EU)	
			AND WORST DETECTION	DETECTION	ш 9	6 m DEPTH	30 m	30 m DEPTH	m 06	90 m DEPTH
	,		REST	WORST	BEST	WORST	BEST	WORST	BEST	WORST
	, , , , ,	YAA (ALONG-TRACK)	°°	009	189	47	7.6	1.9	0.84	0.21
INLINE	π ^π	Yuu (CROSS-TRACK)*	°09	ô	142	<10-5	5.7	<10-5	0.63	<10-5
	$\begin{pmatrix} \gamma_{yy} \end{pmatrix}$	Yyy (VERTICAL)*	ALL	6	189	189	7.6	7.6	0.84	0.84
	, γ _λ γ	γ _{λy} (ALONC-TRACK, VERTICAL)	%	009	123	61	6.9	2.5	0.55	0.27
CROSS GRADIENTS	γ _{γη}	γ _{λμ} (HORIZONTAL PLANE)	450	°°	95	<10-5	3.8	<:0-5	0.42	<10-5
	ر ۲ م	Y (CROSS-TRACK, VERTICAL)*	600	00	108	<10-5	4.3	<10-5	0.47	<10-5
	•									

(NOTE: PEAK SIGNAL STRENGTH BECOMES EXCERDINGLY SMALL FOR 0 = 90°) *ENCOUNTER ANGLES (0) CONSIDERED ARE 0°, 30°, 45°, 60°

CONCLUSIONS

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- GRADIOMETRIC DETECTION OF LARGE TUNNELS TO A DEPTH OF 30 m IS FEASIBLE USING MOVING BASE GRADIOMETERS WITH AN ACCURACY OF 1-10 EU (10 sec AVERAGING TIME) 1-10 EU (10 sec AVERAGING TIME)
- RELIABLE DETECTION OF LARGE TUNNELS DEEPER THAN 30 m IMPOSES MODERATELY SOPHISTICATED NATA PROCESSING REQUIREMENTS (e.g., MULTIPLE COMPARISONS ..MONG GRADIENTS. OPTIMAL FILTERING, SIGNATURE MATCHING, e+c.;
- DETECTION OF TUNNELS DEEPER THAN 90 m IS DIFFICULT
- SINCLE GRADIENT ELEMENT WITH GREATEST CONSISTENT SIGNAL STRENGTH REGARDLESS OF ENCOUNTER ANGLE IS THE VERTICAL, IN-LINE TERM
- AXIAL DIRECTION OF SHALLOW OR LARGE TUNNELS CAN BE ESTABLISHED IN A SINGLE PASS BY COMPARINC MAGNITUDES OF ELEMENTS IN THE GRADIENT TENSOR (SUBJECT TO TUNNEL'S DEPARTURE FROM IDEAL GEOMETRY)
- MODERATE SHIFTS OF SURFACE CROSSING POINT TOWARD ONE END HAVE AN INSIGNIFICANT EFFECT UPON DETECTABILITY



ADDITIONAL TOPICS OF INTEREST

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MAXIMUM DETECTABLE DEPTH USING OPTIMAL FILTERING AND TAKING ALL RELEVANT ERROR SOURCES INTO ACCOUNT

QUANTIFICATION OF CLOSENESS OF DETECTOR VEHICLE TRACK TO AXIAL DIRECTION BEFORE GNSET OF UNOBSERVABILITY

DISTANCE BETWEEN CRASSOVER POINT AND TUNNEL END WHERE MODELED GPADIENTS (GAUSS' LAW + POINT MASS) DEVIATE SUBSTANTIALLY FROM ACTUAL GRADIENTS

MORE COMPLICATED TUNNEL GEOMETRIES, VERTICAL SHAFTS

THE DEPTHS AND ENCOUNTER ANGLES